Accelerating Particles to High Energy

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Outline of Presentation

- How do we accelerate particles?

- How do we keep billions of particles all going around together?

- How do we use accelerators to do High Energy Physics experiments?

- Fermilab Accelerators and their Operation

- The Future

Why Do We Need Accelerators?

- Kids probably tell their parents that they ***need*** these:

    TV's!   (classic TV's; not LCD display or plasma TV, though…)

- Other 'needs' in everyday life might include
    - Medical applications: X-ray machines, PET scans, etc.
    - Industrial applications
        - e^- beam welding, semiconductor modification, etc.

- In fact, a study in 1994* showed there were about 10,000 accelerators world-wide at that time:
    - only about **112** were used for 'High Energy' Physics!
    - ~5000 biomedical, ~4900 industrial
    - (does not include TV's!   ;-)

*Scharf & Chomicki, *Physica Medica* XII(4), 1996.

So, why do *we* need Accelerators?

- That is, why high energy particle accelerators, like at Fermilab?
- How do we "see" things?
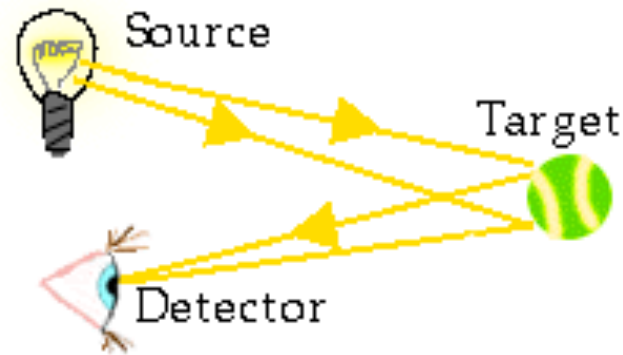
- We need to send source particles toward target particles and then detect the outcome.
- "High energy" particles can have their energy converted into mass ($E = mc^2$), and so new particle states can be created and observed.
- In addition, accelerators provide the ability to control the particles (steer, focus, increase/decrease intensity, for instance) in order to conduct experiments efficiently and in a controlled fashion.

How to Accelerate Particles

Acceleration

- Dictionary Definition

  acceleration |ak͵selə'rā sh ən|

  noun
  increase in the rate or speed of something : *the acceleration of the industrialization process*
  - **Physics: the rate of change of velocity per unit of time.**
  - a vehicle's capacity to gain speed within a short time : *a Formula One car is superior to an Indy car in its acceleration.*

- Newton's Second Law (one version):
  $$a = F/m$$ = Force delivered divided by mass of the object

Early Particle Accelerator

g

"Gravitational Field"

- Force -- due to gravity (*weight*) $F = mg$

- Energy gained = Force applied times distance traveled $= mg \cdot h$

- If started from rest, kinetic energy is gained,

$$\Delta E = \frac{1}{2}mv^2$$

From the tower, ...

$$v = \sqrt{2gh} = \sqrt{2(32)(183)} \text{ ft/sec} \approx 100 \text{ ft/sec} \approx 70 \text{ mi/hr}$$

"Particle Acceleration"

- Sub-atomic particles are lightweights! A little force gets them going very fast!

- But, gravity isn't strong enough for our purposes

  - electrons, protons, etc. are electrically charged particles, and influences of electric and magnetic fields are much, much stronger than gravity

  - we want to get them moving near the speed of light

- So, set up electric fields (force) to accelerate them...

demo...

How to Accelerate Charged Particles
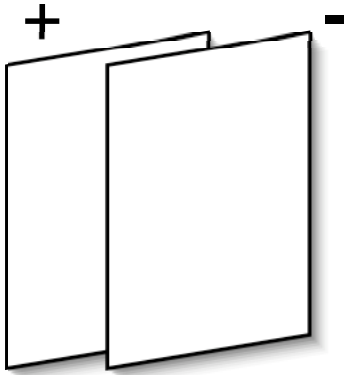
$$|\vec{E}| = V/d$$

$$|\vec{F}| = q|\vec{E}| = qV/d$$

amount of charge

"Electric Field"

$\vec{E}$

$\vec{F}$ ← e^-

d

9v

As the electron accelerates from the right hand plate to the left, the change in **energy** is the work done (force times distance),

different *E!*

$$\Delta E = F \times d = qV$$

The charge on an electron is $q = -e = -1.6 \times 10^{-19}$ Coul

(on a proton, $+1.6 \times 10^{-19}$ Coul $= +e$)

So, we say that an electron/proton accelerated through 1 volt gains an amount of energy $\Delta E = 1$ eV (1 **electron volt**) (= 1.6×10^{-19} J) In example above, the electron would gain energy of amount **9 eV**.
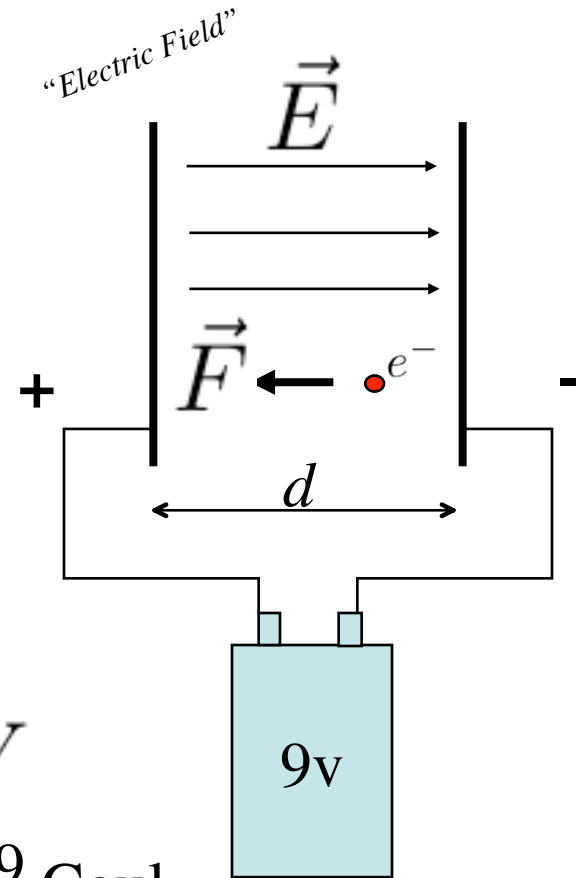
How fast is this electron moving?

If started from rest, $\Delta E = \frac{1}{2}mv^2$, and so $v = \sqrt{2\Delta E/m}$

$$= \sqrt{2 \times 9(1.6 \times 10^{-19}J)/(9 \times 10^{-31}kg)} = 1.8 \times 10^6 \text{ m/s!}$$

This is   4 million miles/hr !   = 0.6% the speed of light (0.006c)

(c = 186,000 miles/sec = 300,000 km/sec)
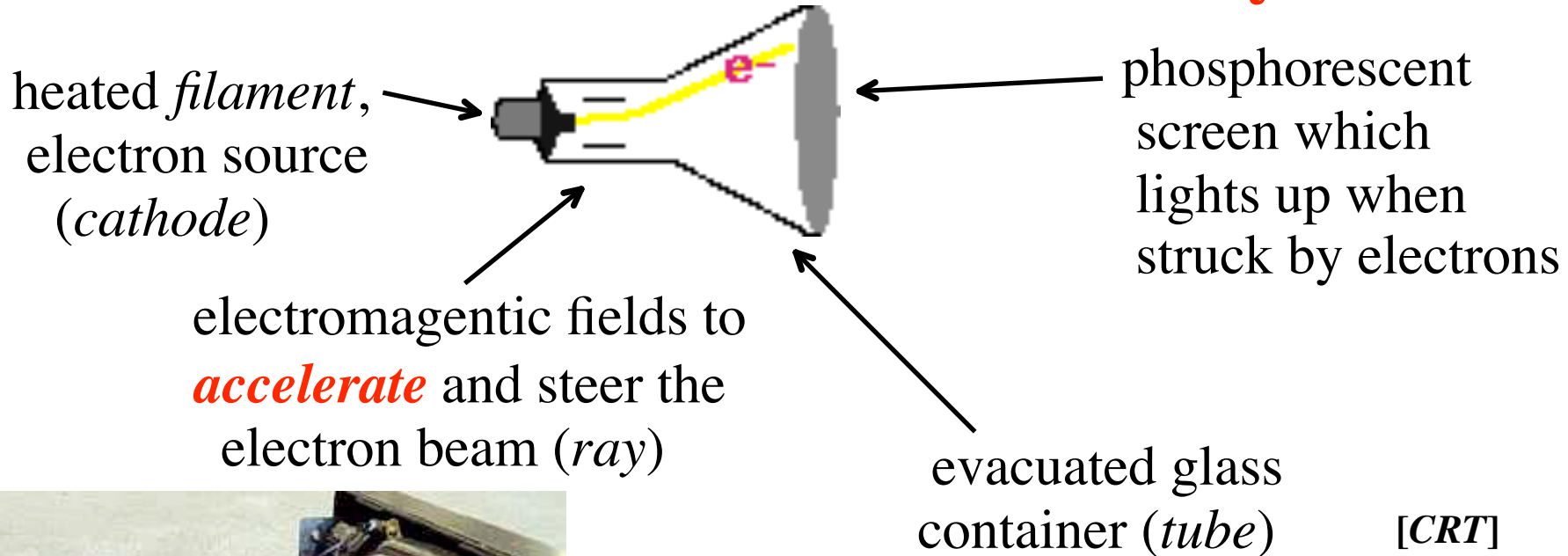
Note: if looked at a proton instead, its mass is 1836 times that of the electron. Thus, its speed would be *only* 0.00014c.

(= 90,000 mi/hr!)

Q: How much voltage can we deliver?   Let's look at a TV set...

Your TV Set

- The "classic" television is a **Cathode Ray Tube**

heated *filament*, electron source (*cathode*)

e⁻

phosphorescent screen which lights up when struck by electrons

electromagentic fields to *accelerate* and steer the electron beam (*ray*)

evacuated glass container (*tube*)   **[*CRT*]**

OK, so it's a *little* more than that… but not much!   *Really*!

Note: voltages encountered are a few tens of thousands of volts, therefore particle energies of about **10,000 eV**!

So, how fast are we moving now?

- An electron in a typical TV set, with **10 keV** kinetic energy, say, would thus be moving about

  $$(10{,}000 \text{ eV} / 9 \text{ eV})^{1/2} = 30 \text{ times faster, --> } \textbf{\textit{20\% c}}.$$

- Does this mean a 250 keV electron would be moving *at* the speed of light? Can we go faster?

  - No! "Relativistic effects" kick in…

    – Einstein, in 1905, showed that we had to modify our definitions of momentum and energy when near light speed

    – His Theory of Special Relativity (*near the speed of light*) plays a big role in high energy particle acceleration

Speed, Momentum vs. Energy

speed
v/c

Kinetic energy
gamma - 1

momentum
gamma * (v/c)

Kinetic energy
gamma - 1
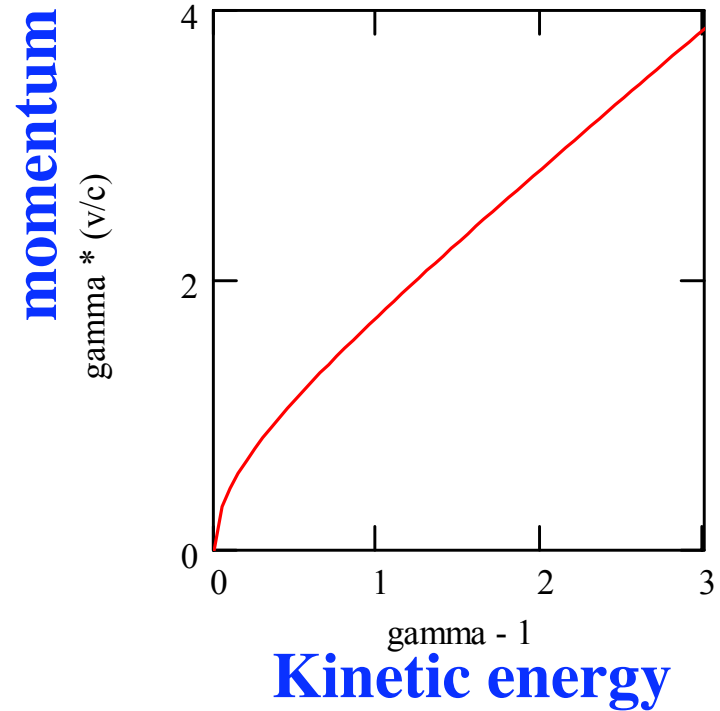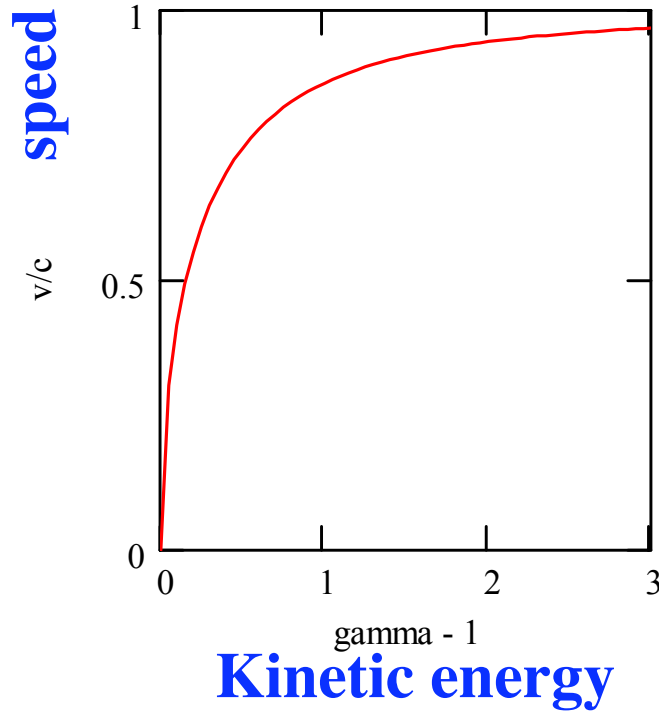
Electron: 0   0.5   1.0   1.5   MeV
Proton: 0   1000   2000   3000   MeV

$$gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

rest energy, mc^2:

e-   0.5 MeV
p   938 MeV

So, Back to High Voltage!

- How to get **high voltage**? How high can we go?
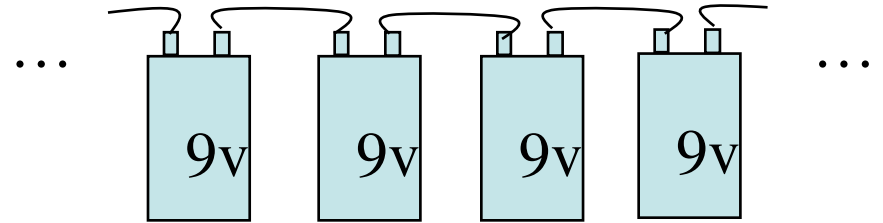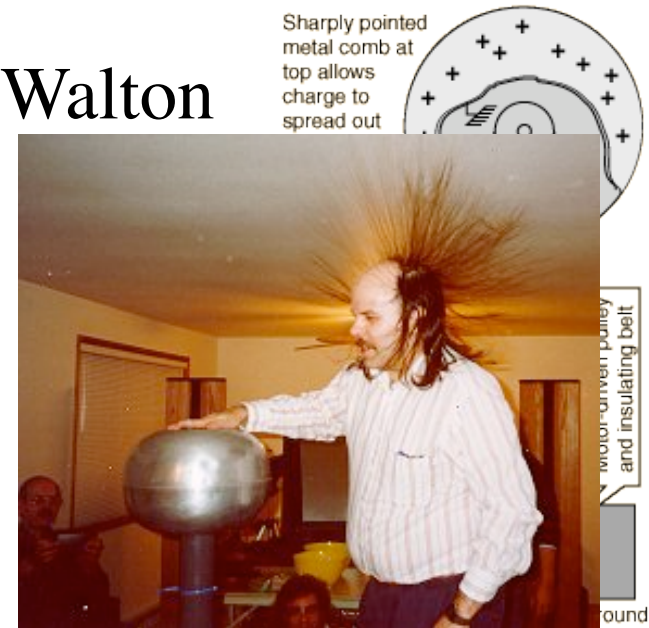- String a bunch of batteries in series!
  - Not very practical…
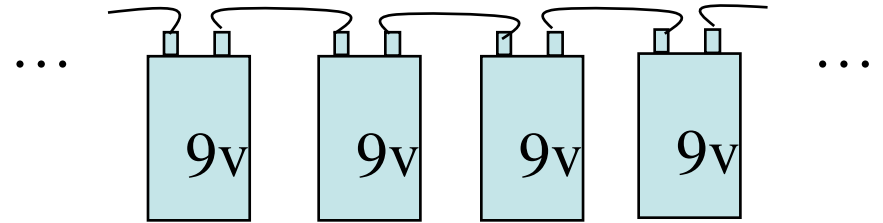
- High voltage Generators
  - Ex: van de Graaf, Cockcroft and Walton
- The *van de Graaf* Generator:
  - probably familiar …
  - static electricity

  (as shown -- 75,000 V!)

So, Back to High Voltage!

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- String a bunch of batteries in series!
  - Not very practical… ... 9v 9v 9v 9v ...

- High voltage Generators
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  - probably familiar …
  - static electricity

  (as shown -- 75,000 V!)

Sharply pointed metal comb at top allows charge to spread out

motor-driven pulley and insulating belt

round

High Voltage

- van de Graaf's are used for particle accelerators (though, with a different configuration) and provide voltages up to ~10,000,000 V = 10 MV.

- Fermilab has a related device, called a Pelletron, which works on the same principle; produces electron beams with energies of about 4 MeV.

- Another device was developed in early 1930's by *Cockcroft and Walton,* and is named after them:
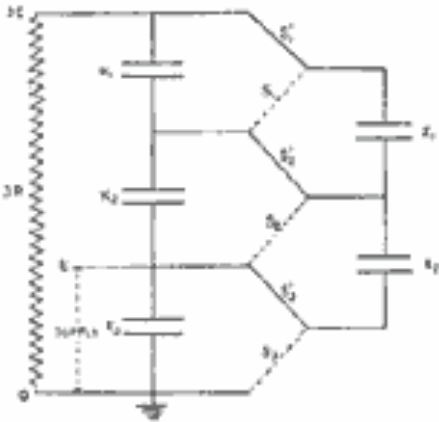
Converts AC voltage V to DC voltage n x V

Is that Cockcroft, or Walton??
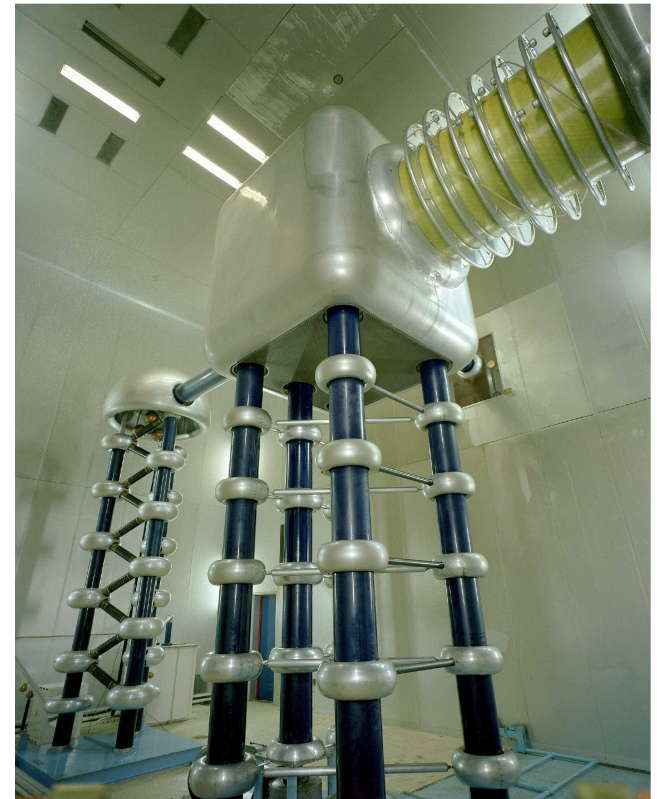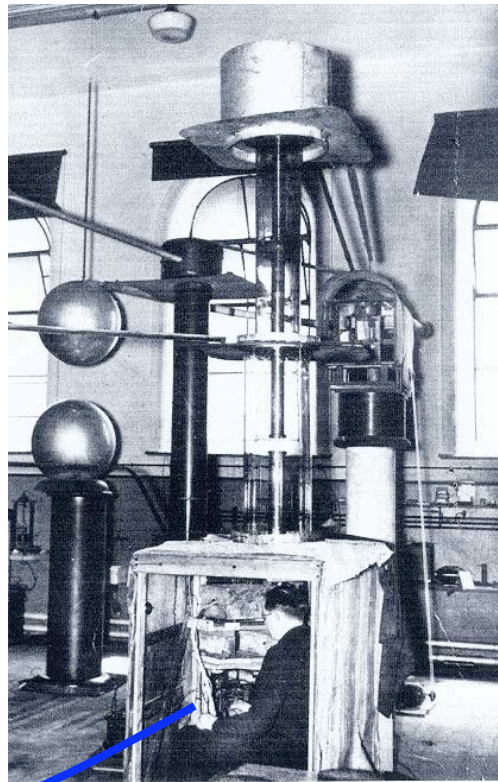
Let's Re-use the E-field!

- The Cockcroft-Walton design can produce voltages up to a few MV, and the van de Graaf up to about 10 MV; at these voltages, materials begin to experience "high voltage break-down"

  – Takes only a few MV to generate lightning

- So, to continue to higher particle energies, would like to re-use the electric fields we generate:
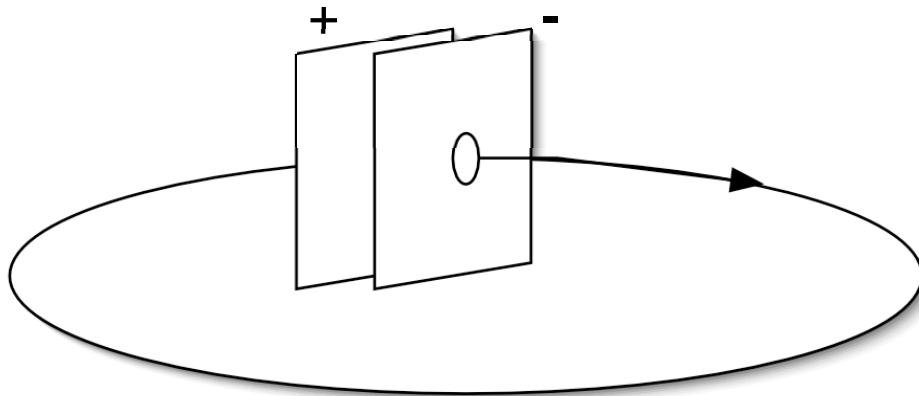
BUT!   If the voltage is DC, then though particle is accelerated when in between the plates, it will be *decelerated* while outside the plates!
       -- *net acceleration* = 0 !
SO, need a field which can be switched on and off -- an AC system!

Circular Accelerators

- First circular accelerator was the cyclotron
  - Since the entire cyclotron had to be in a magnetic field, the magnets would become very large.
  - Also, as the particles continued to accelerate, their speeds would begin to approach c, and thus they would not keep in step with the changing voltage.
- "Synchrocyclotrons" were invented to try to take these effects into account, as well as other types of accelerators -- betatron, microtron, …
- But the one that won out, when it came to very high energy particle beams, was the *synchrotron*.

The Synchrotron

- Use a single device which develops an electric field along the direction of motion, and which oscillates at a tunable frequency.

- Use a series of tunable electromagnets whose strength is adjusted to keep the particle(s) on a circular orbit back to the accelerating device (cavity).
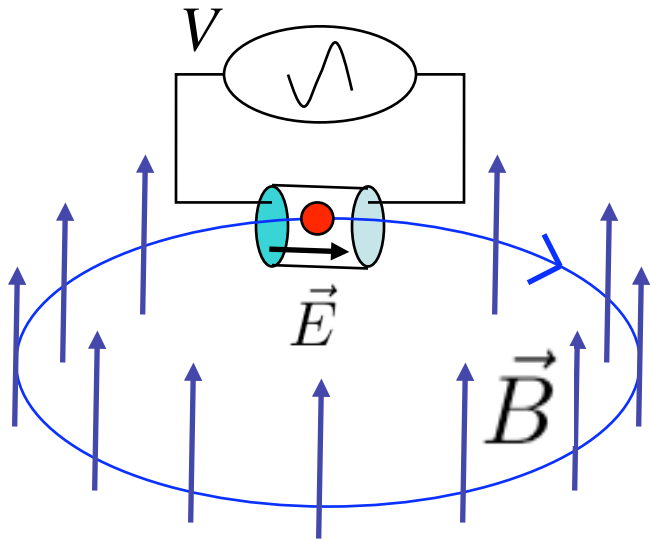
Voltage $= V \sin(2\pi f\, t + \delta)$

$f = 1/T = v\, / \, 2\pi R$

Each revolution,
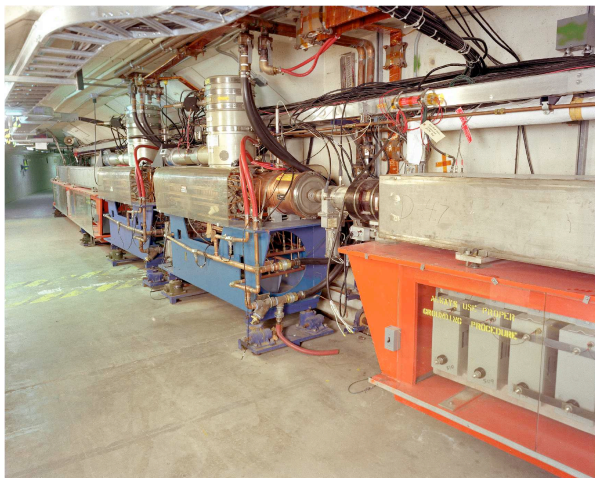 energy changes by amount
  $\Delta E = e\, V\, \sin(\delta)$

δ is called the *synchronous phase angle*

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Synchrotrons at Fermilab
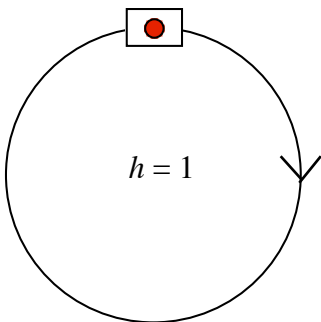
Booster

$R = 75$ m

$h = 84$

Main Injector

$R = 500$ m
$h = 588$

All use
53 MHz
systems

$h = \#$ possible 'bunches' in
the accelerator
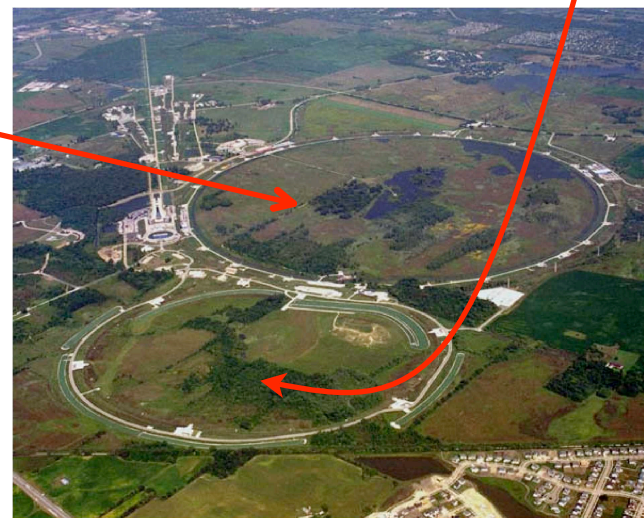
Radio Frequencies, or "RF"
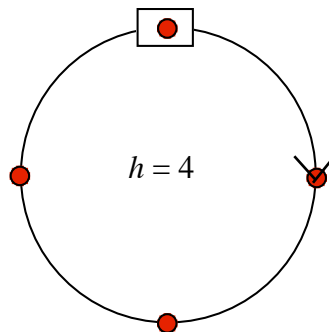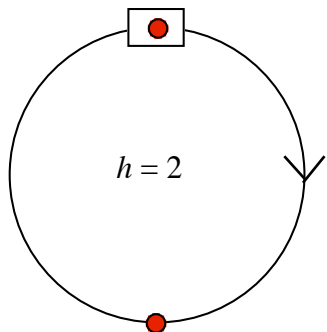
Tevatron

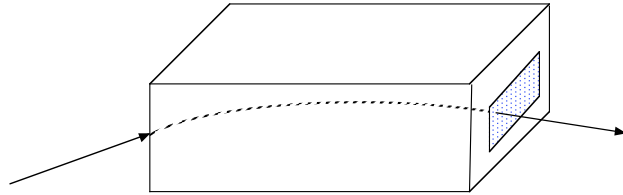$R = 1000$ m
$h = 1113$

$h = 1$

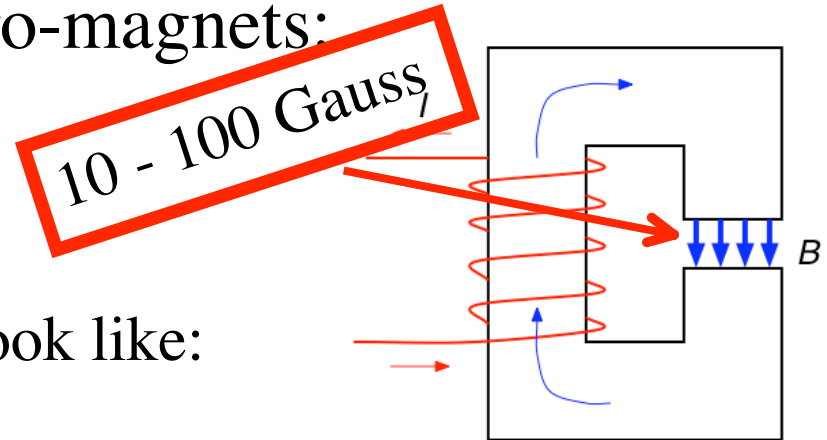$h = 2$

$h = 4$

So much for acceleration, ... what else do we need?

demo...

Accelerator Magnets

- To steer **high energy**, charged particles, we need to use strong magnetic fields -- electro-magnets:

10 - 100 Gauss

- A simple electromagnet might look like:
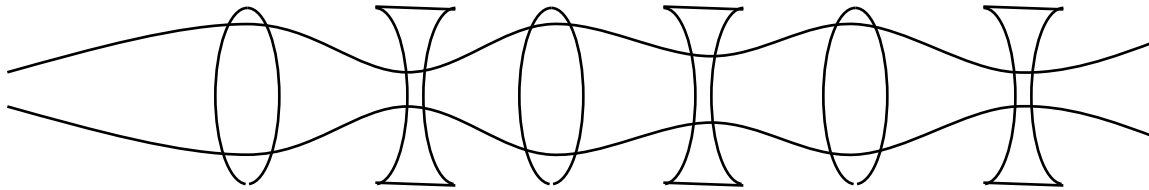
- Accelerator magnet:
  - lots of current and lots of iron!
    - Iron-dominated magnets can obtain field strengths up to ~2 Tesla

20,000 Gauss!!

Focusing

- So, as particles move around the accelerator, we need to use other electromagnets to steer and focus them

- Arrangement of focusing magnets, acting much like optical lenses, keeps the particle beam contained…

- Smaller magnets are used to fine-tune the beam trajectory, and to perform special orbit manipulations
  - Note: The beam in the Tevatron, for example, is only about 1 mm wide! Its orbit is controlled to a fraction of a mm! Yet, the orbit itself is 6.28 km (4 mi) around!
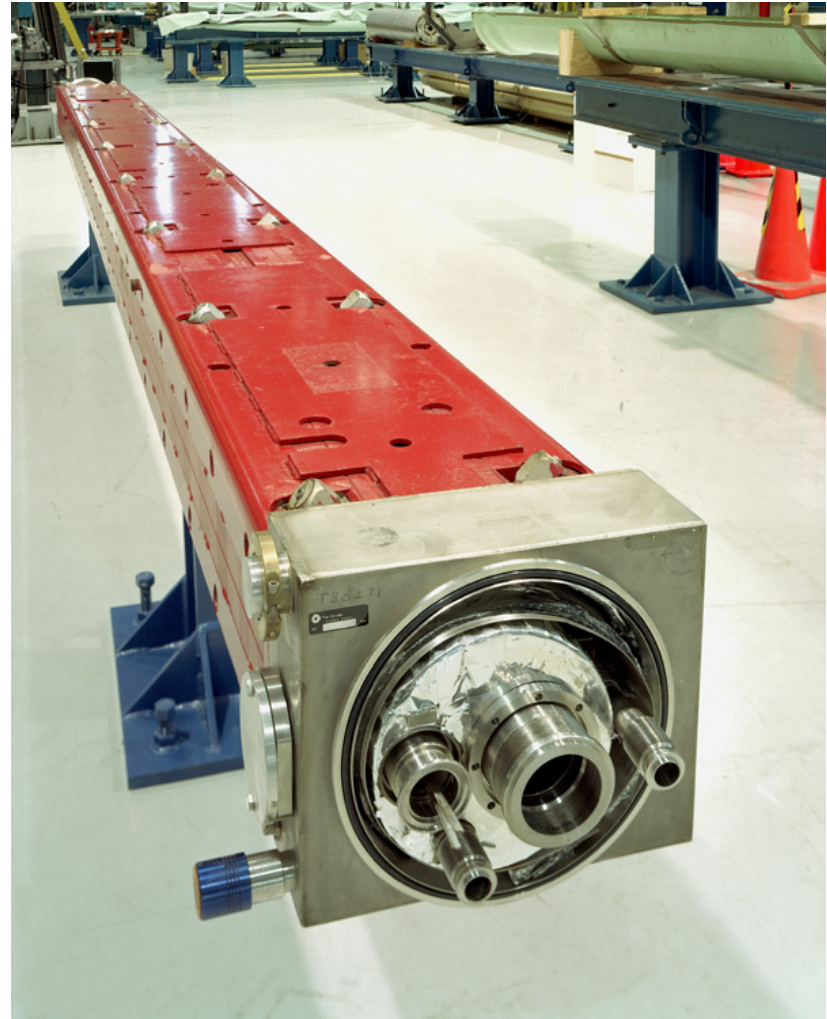
Example: Fermilab Main Injector

Bending Magnets

Focusing Magnets
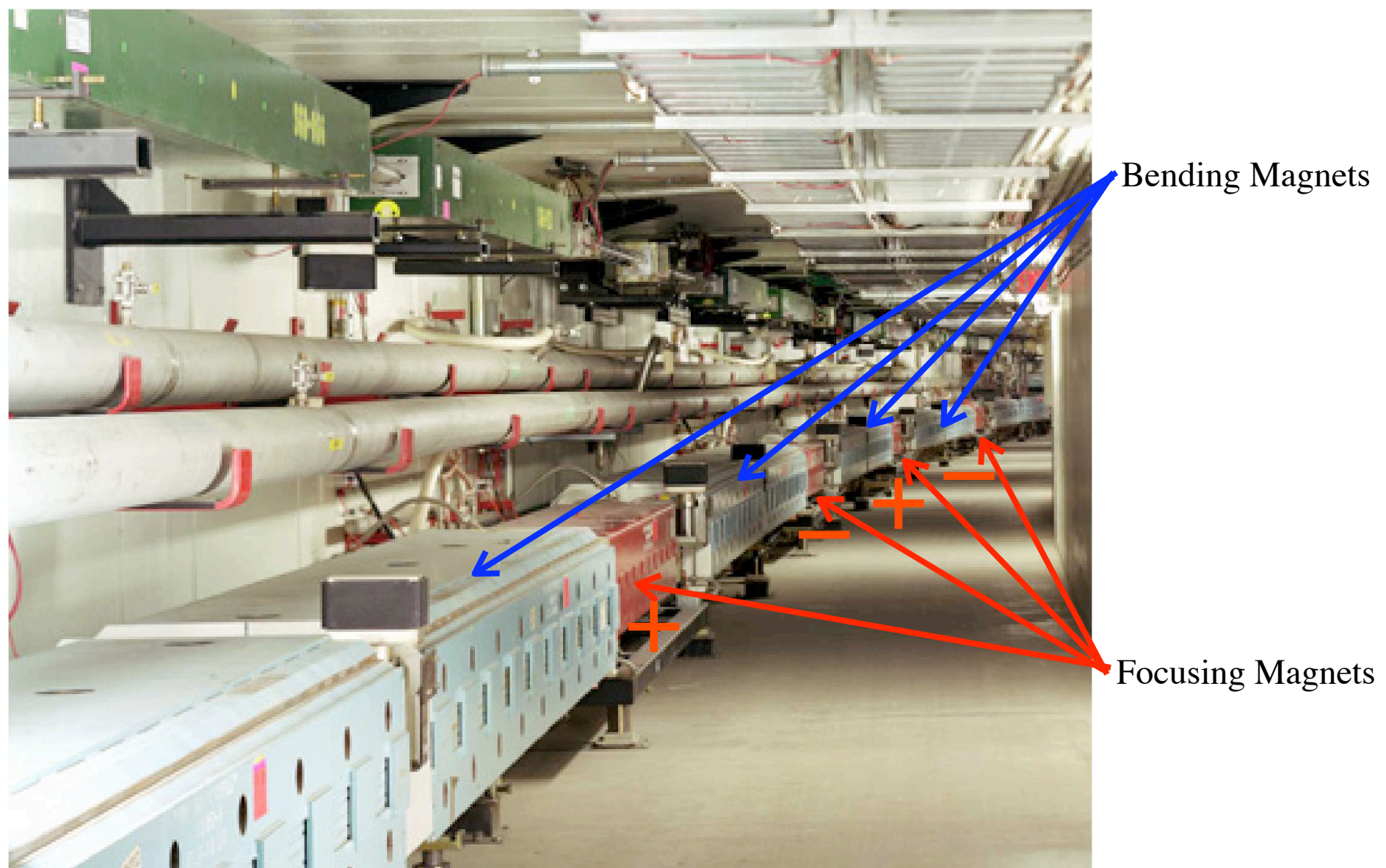
Superconducting Tevatron Magnet
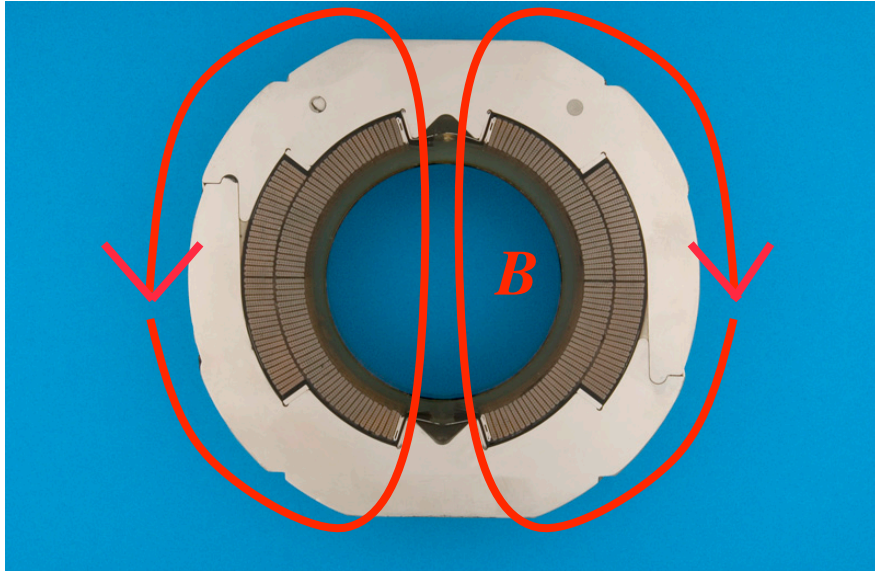
- Outside is at room temperature; inside is at $4^{\circ}K$!
- Field is **4.4** Tesla @ ~4,000 A
- Each magnet is ~20 ft long, and weighs about 4 tons
- ~1000 magnets in the Tevatron

How Accelerators are Used at Fermilab

- Collide beam of particles into a stationary target
  - Neutrino experiments, for example
- Collide beams of particles moving in opposite directions:
  - The energy of the collision can be used to produce new particles   (mass = energy!)
  - Energy and Momentum must be conserved
  - Einstein: $E^2 = (mc^2)^2 + (pc)^2$
  - **Collider**: zero momentum before AND after. Thus, *ALL* energy can be converted into *new stuff*!
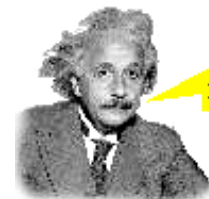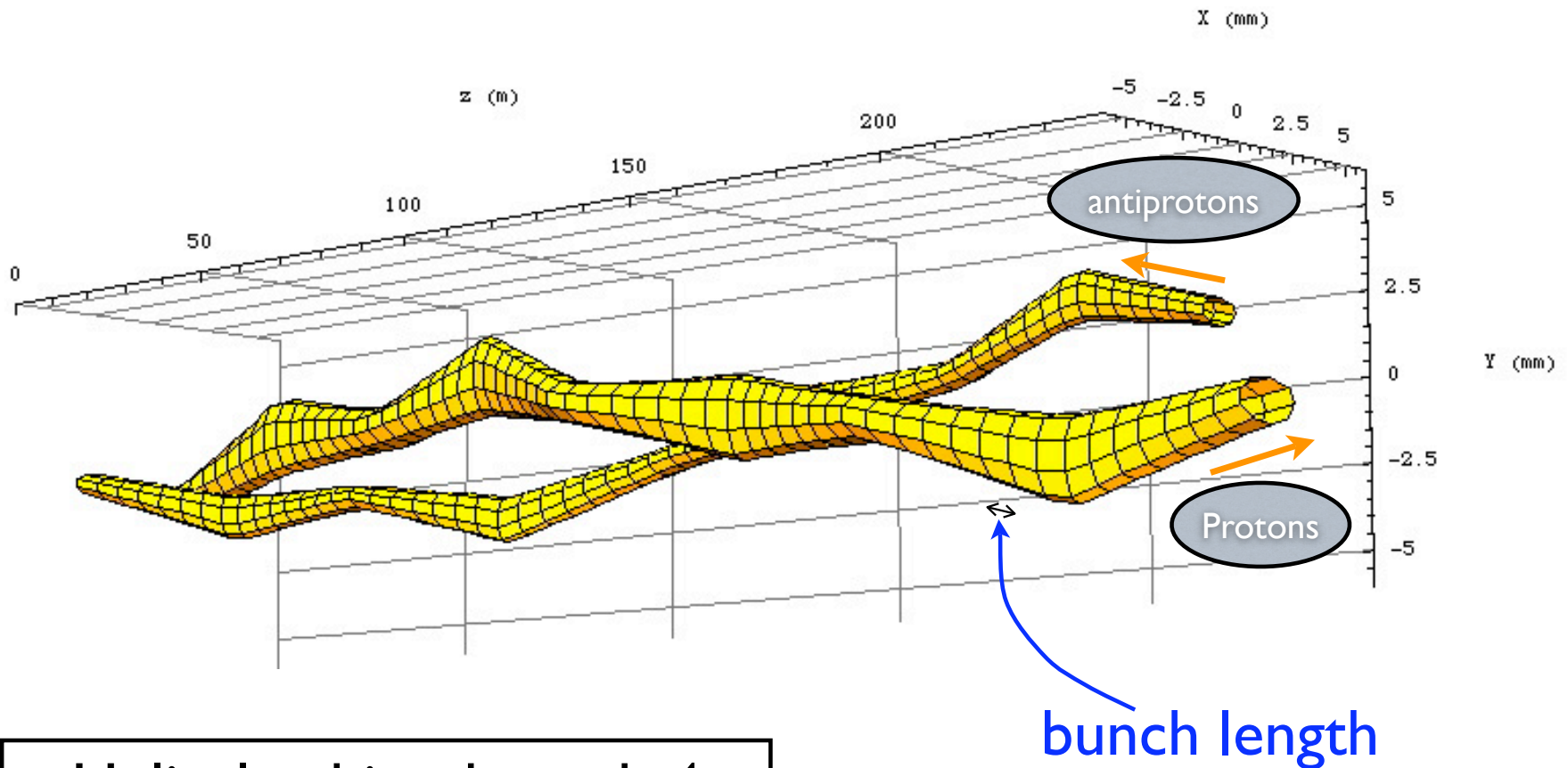
Mass is just a form of energy!

Tevatron Collider

Tevatron Collider

Tevatron Beam Envelopes

Helical orbits through 4 standard arc cells

Squeeze Play…

Beam Shape through Final Triplets

protons →

antiprotons ←

Beam Size

Distance from Interaction Point (m)

— Horizontal out
······ Vertical up
— Quad Magnet
— Horizontal in
······ Vertical dn

We change the strengths of quadrupole magnets to focus the beam stronger, thus increasing chance for collisions

Some Numbers…

- For Tevatron operation,
  - $N_{protons} = 300 \times 10^9$, $N_{antiprotons} = 70 \times 10^9$,
  - $f = 36 \times (3 \times 10^5 \text{ km/sec})/6 \text{ km}$,
  - $A = \pi (60 \text{ } \mu m)^2 = \pi (0.0060 \text{ cm})^2$
  - ---> *luminosity*: $L = 3 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$

- Cross section of a proton/antiproton collision

  $$\sim 6 \times 10^{-26} \text{ cm}^2$$

- So, we get, and wish to detect, about 18×10^6 collisions per second!
  - The Collider detectors must be able to gather, examine, sort, store relevant data at this rate (and they do!)

- Each proton/antiproton has energy of

  $$980 \text{ GeV} = 980 \times 10^9 \times (1.6 \times 10^{-19} \text{ J}) = 1.6 \times 10^{-7} \text{ J}$$

- So, *power* delivered in the collision region is only about

  $$2 \times 1.6 \times 10^{-7} \text{ J} \times 18 \times 10^6 \text{ /sec} \sim 6 \text{ watt!}$$
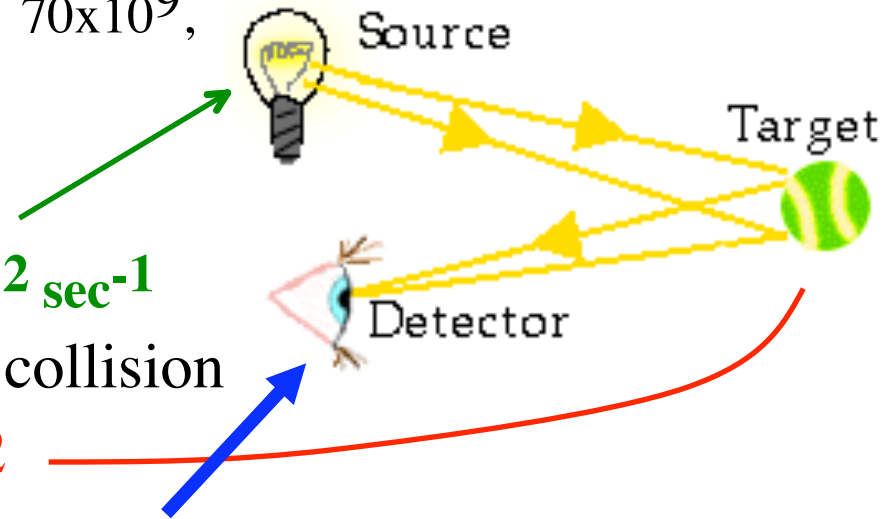
Daily Operation

- Put a "store" into the Tevatron, to produce collisions of protons and antiprotons at ~1 TeV/particle
  - lasts for ~18 hr
- Use the Main Injector to...
  - Make more anti-protons
    - $\sim 300 \times 10^9$/hr
  - Make and send Neutrinos to ...
    - Minnesota
    - on-site detector
  - Send protons to a "fixed target" facility
   - 0.12 TeV protons onto targets
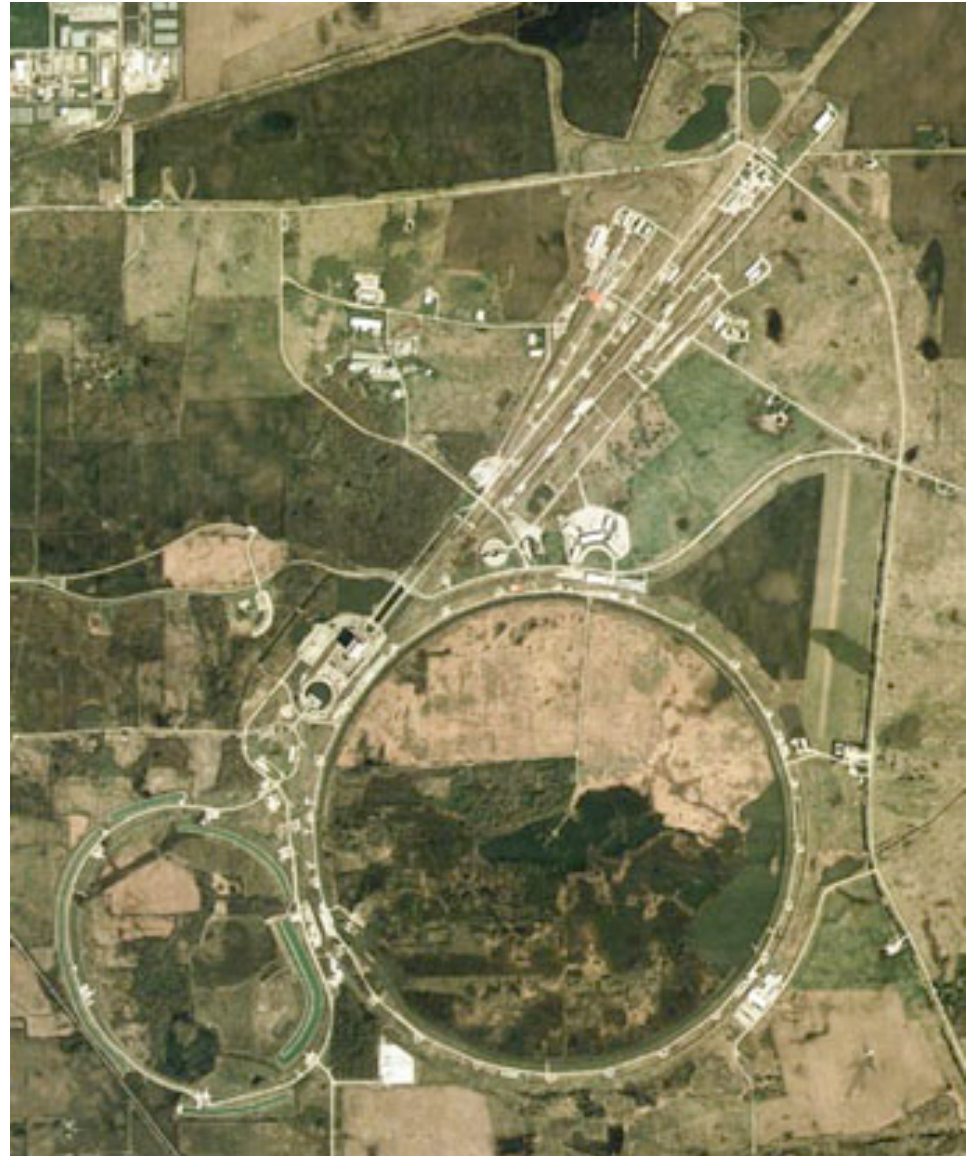
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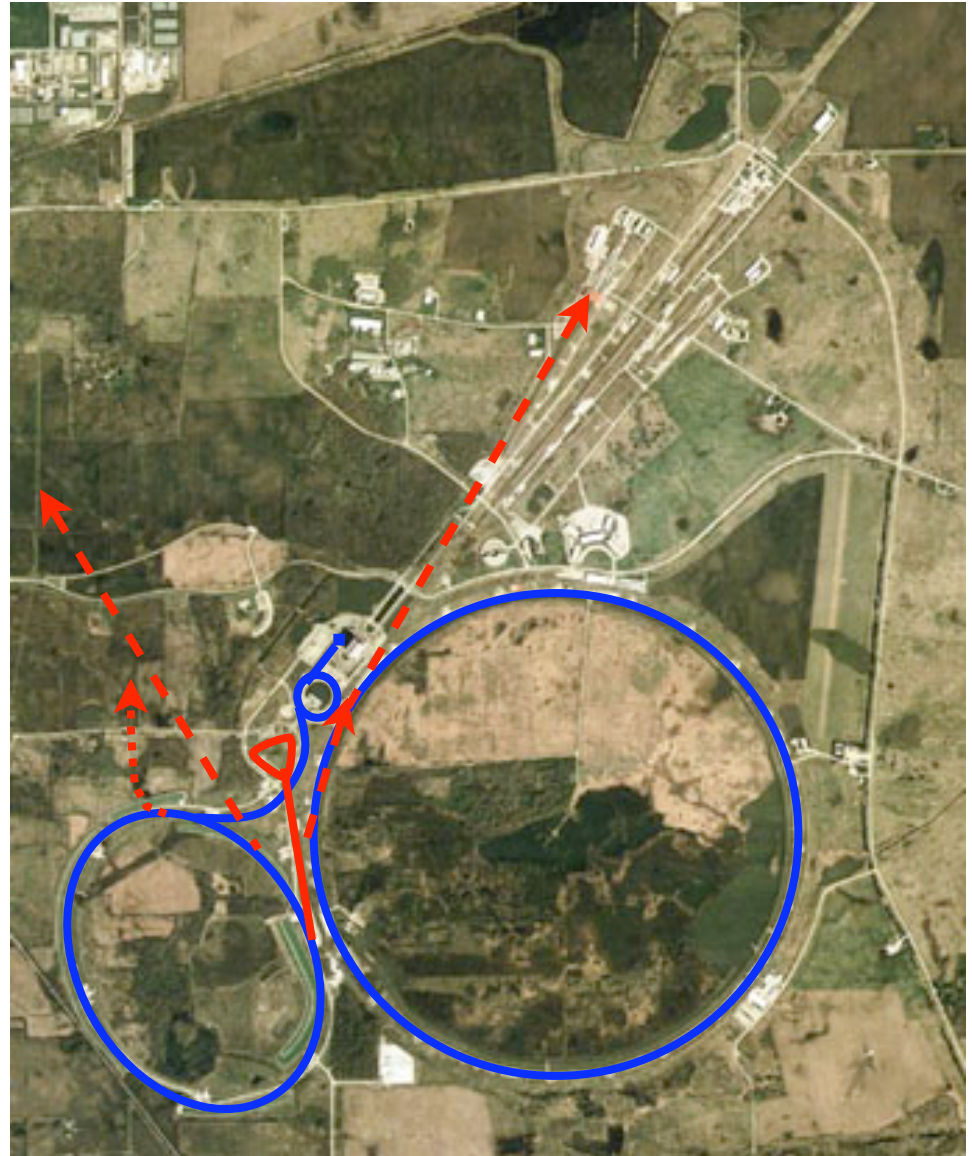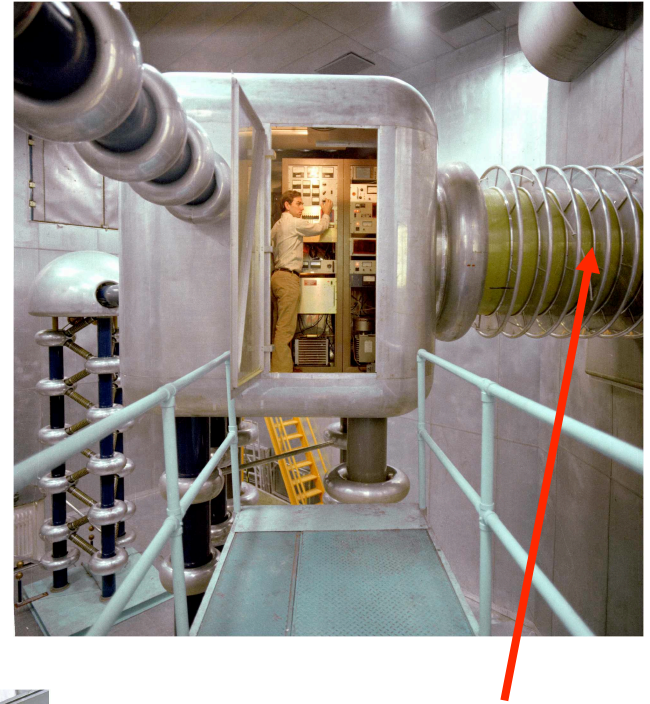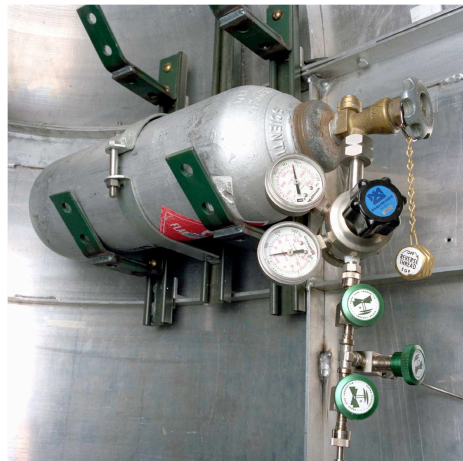
Cockroft Walton Preaccelerator
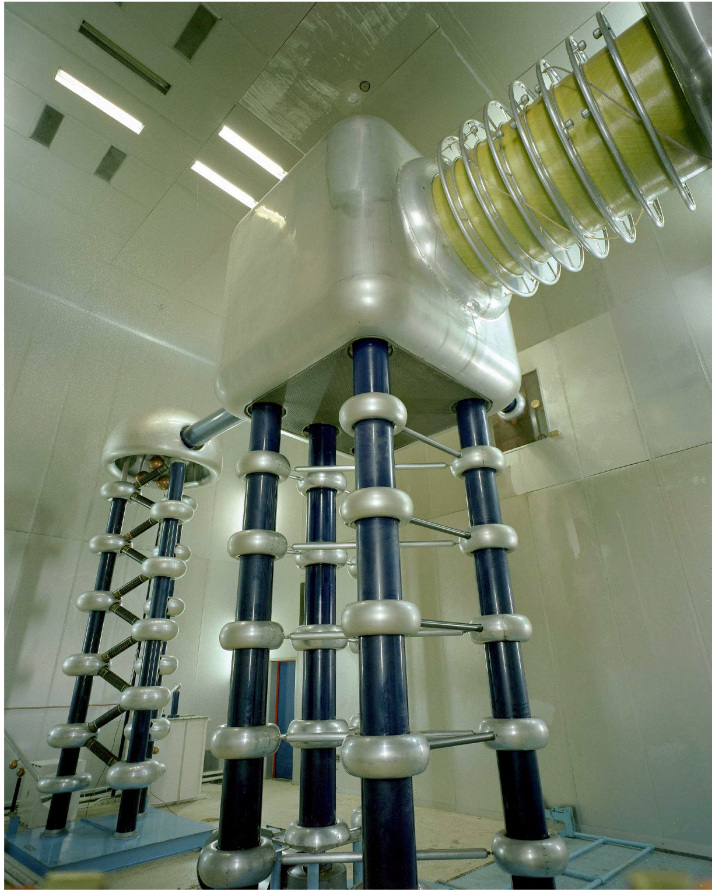
All starts here!

inside the dome:

Begins with a bottle of hydrogen gas, H_2, which is combined with Cesium to produce H- ions

$$(1\ p^+ + 2e^-)$$

Final kinetic energy of the ions is 0.75 MeV, and their speed is ~ 0.04c

The H- ions are attracted toward the wall, through the column, and thus gain speed/energy
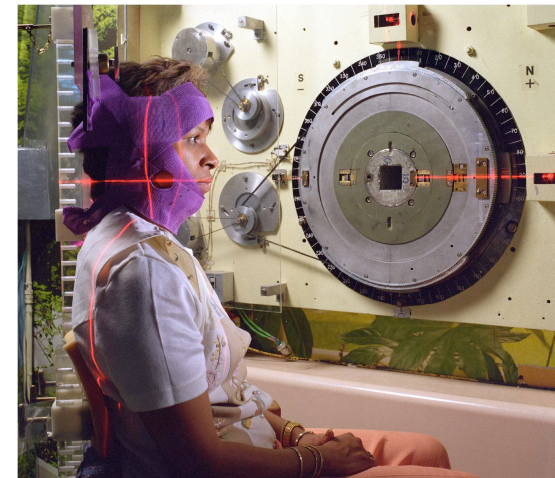
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Linac (cont'd)

Downstream end of Linac:
- particle speed approaching $0.7c$
- gap spacing not changing much; use different cavity structure

- here, field oscillates at 800 MHz
- Total Linac length: 145 m (475 ft)
- Final kinetic energy: 400 MeV

Mid-way, can take particles out and direct toward target; forms neutrons; used for cancer therapy!
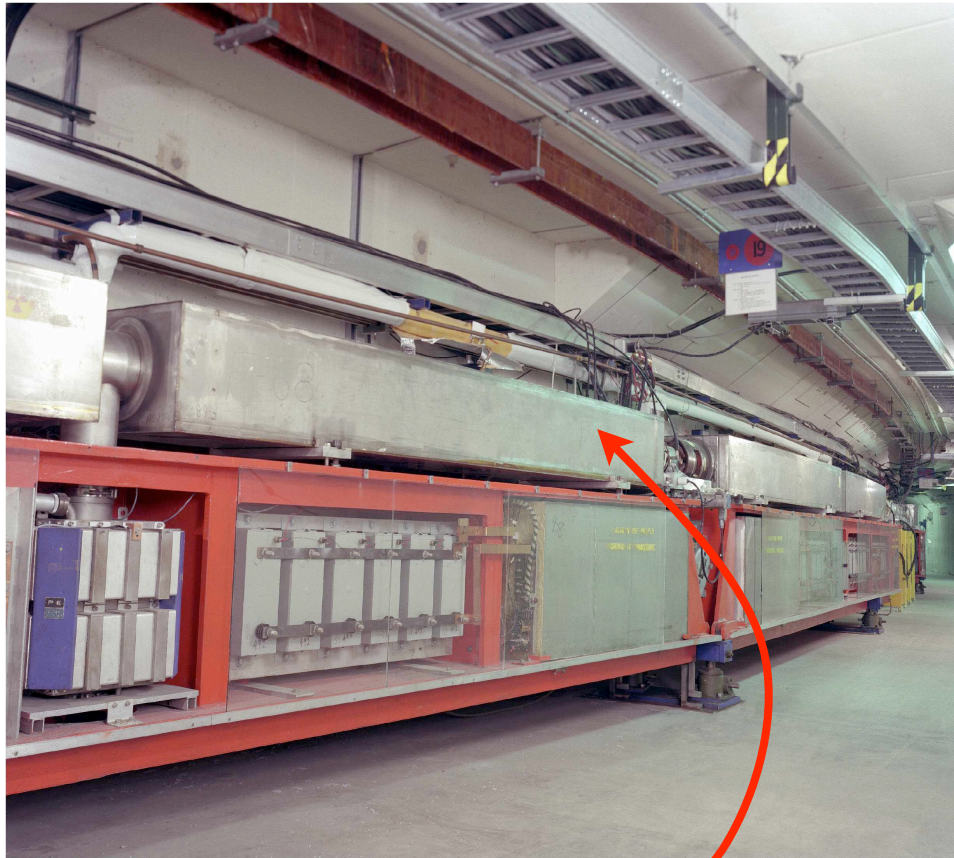
Booster Synchrotron

At entrance, electrons are stripped away from the H^- ions -- leaving protons!

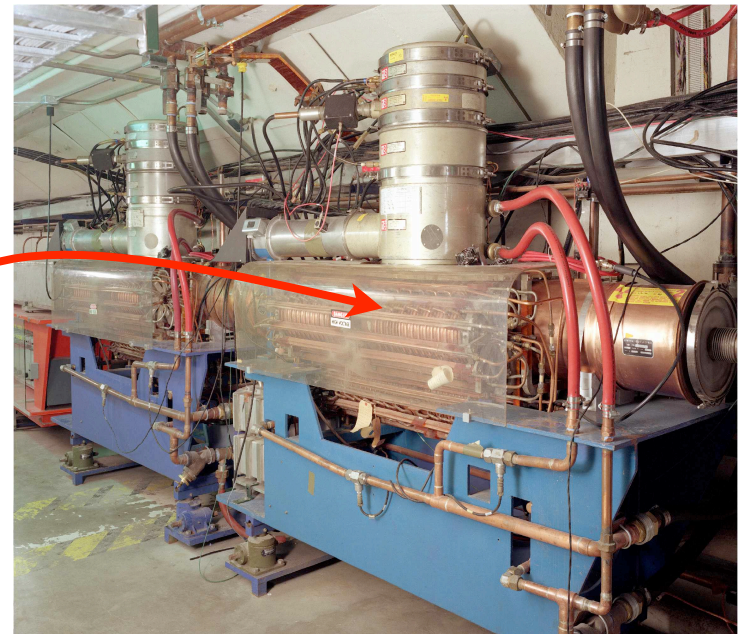Protons circle the Booster 20,000 times, and gain 7600 MeV in K.E.
    they exit traveling at 99% c !
    Total process takes **0.033 seconds!**

Magnets

RF accelerating cavities

Main Injector
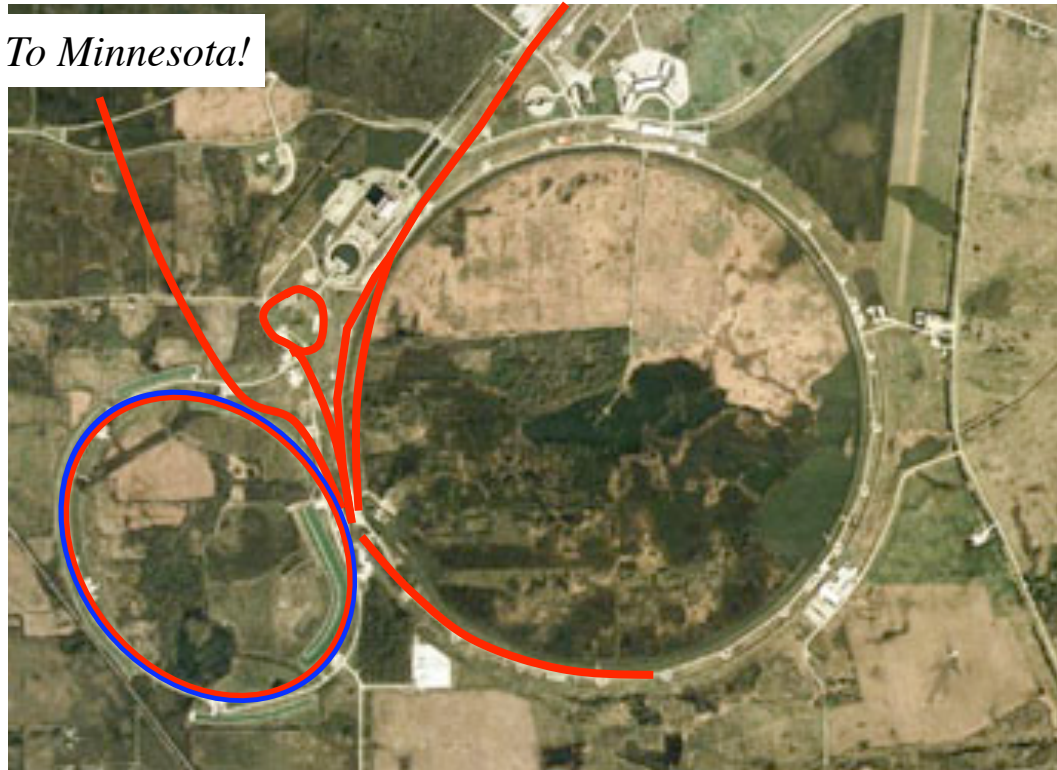
Particles enter with 8 GeV K.E.; accelerate up to 150 GeV ($0.9999c$)

Many uses…

- Protons to Antiproton Source, to make antimatter
- Antiprotons into the Recycler synchrotron for storage
- Protons and Antiprotons to the Tevatron for collisions
- Proton beam to the Test Beam experimental area
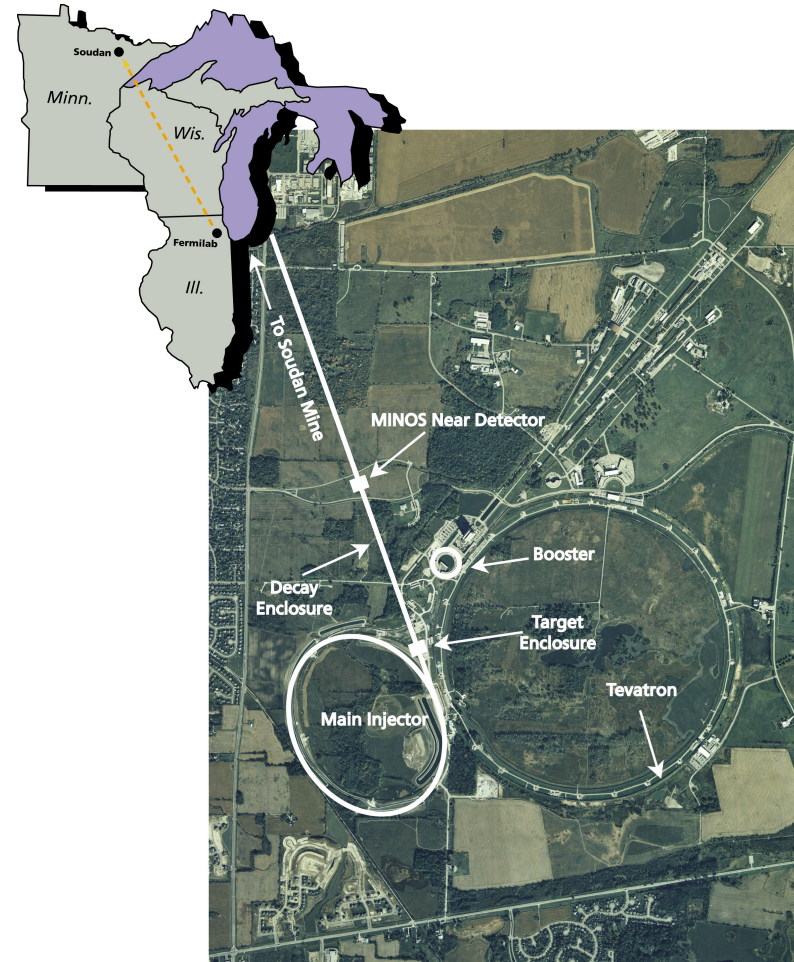- Proton beam for neutrino oscillation experiment (NuMI/MINOS)

magnets

RF:
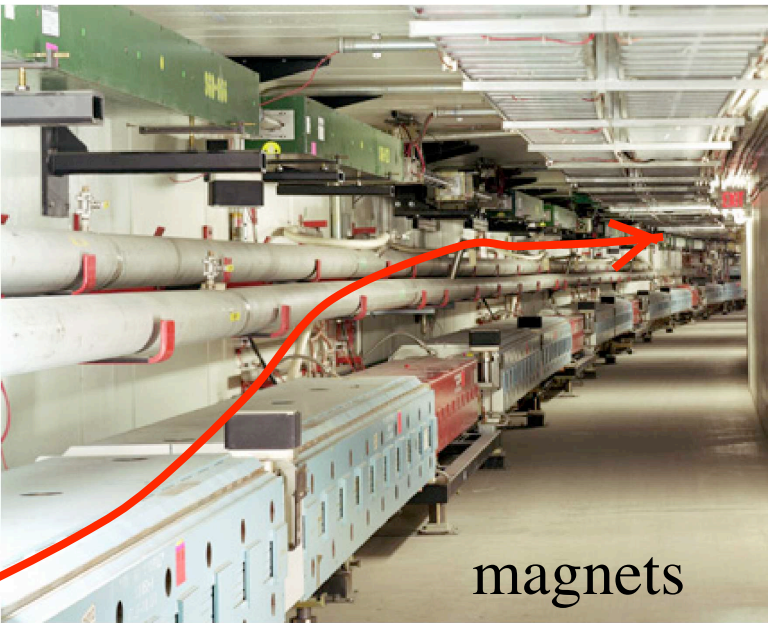
To Minnesota!

Neutrinos at the Main Injector

NuMI Tunnel Project

FERMILAB #98-1321D
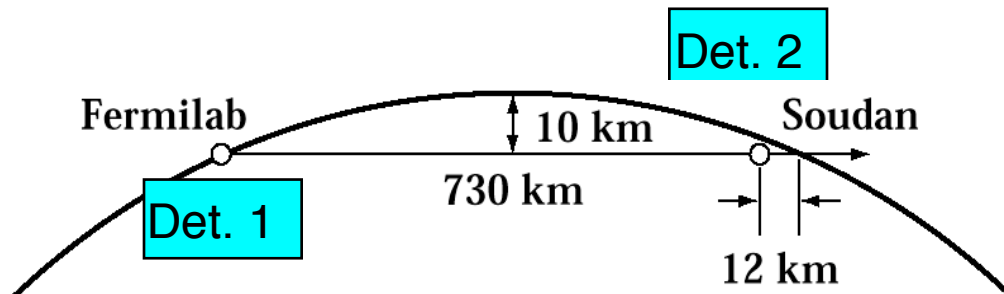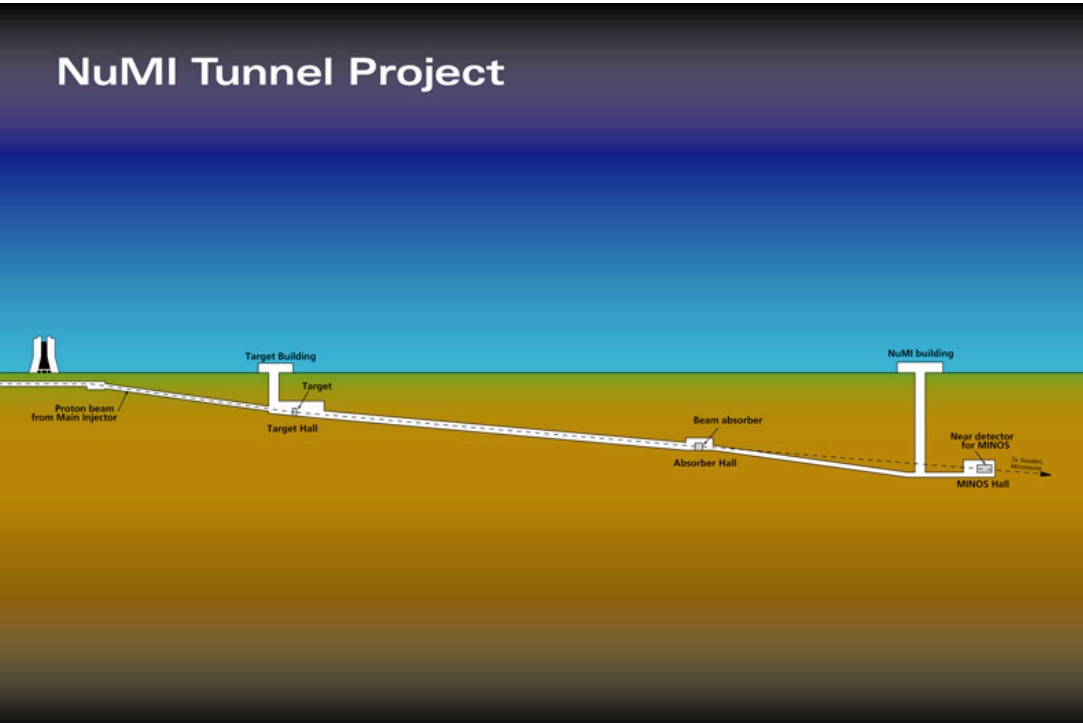
Search for neutrino oscillations (mass)
Sending neutrinos straight through the earth to Minnesota!

Antiproton Source -- anti-matter!

- 120 GeV proton beam from MI strikes target, produces LOTS of particles, every 2 seconds or so
- 8 GeV antiprotons 'filtered' out and stored
- Stochastic Cooling system works on the beam, reducing its size and allowing room to grab/store more particles
- After about 10 hours or so, have ~2-3 Trillion antiprotons!   Send to the Collider!

Recycler Synchrotron

- Resides in Main Injector tunnel, near ceiling
- More efficient to store antiprotons previously conditioned in the Antiproton Source, and *then* send to the Tevatron -- provides higher luminosity overall when used this way
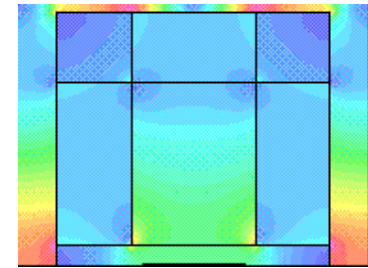 - Can store up to ~6 Trillion antiprotons
  - Permanent magnets are used -- not electromagnets (since beam is stored at one energy -- 8 GeV)
  - Has been used successfully to set luminosity records in the Tevatron

Permanent Magnet field map
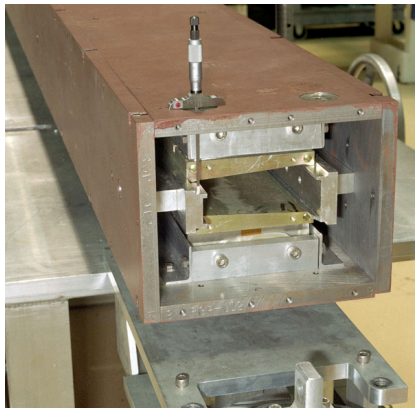
magnet

Pelletron

The Tevatron

- World's Highest Energy particle accelerator -- 0.98 TeV
  - **Still**!   Commissioned in 1983
  - Replaced 400 GeV "Main Ring" in the same tunnel (built ~1972)
  - 1st superconducting accelerator
  - Circumference =
       2π km (+/- 5 cm!)   (~ 4 miles)
  - At 1 TeV, protons, antiprotons
       speed is *99.99996% c* !
  - One round trip for a proton takes
       21 μsec (48,000 revolutions/sec)
- Acceleration takes place with
  8 RF cavities, total ~20 m.
  Rest of circumference is
  magnets, bringing particles
  back to the cavities!

The Tevatron (cont'd)

Colliding-Beam Experiments

- Two beams (matter & antimatter!) circulate in opposite directions, only few mm apart, brought into collision at two detector regions

- While collisions only generate a few watts of power, as shown earlier, the stored energy of the proton beam is

  - $36 \times (300 \times 10^9) \times (1000 \times 10^9 \times 1.6 \times 10^{-19}$ J$) =$ **1.7 MJ** !

    - 1.7 MJ = kinetic energy of a 6 ton truck moving at 60 mph
    - 1.7 MJ ~ 2 jelly doughnuts

  - If lost in one revolution, instantaneous power: 1.7 MJ / 21 μsec = **80 GW**!

- Soon, CERN's LHC will take over as world's most powerful accelerator ...
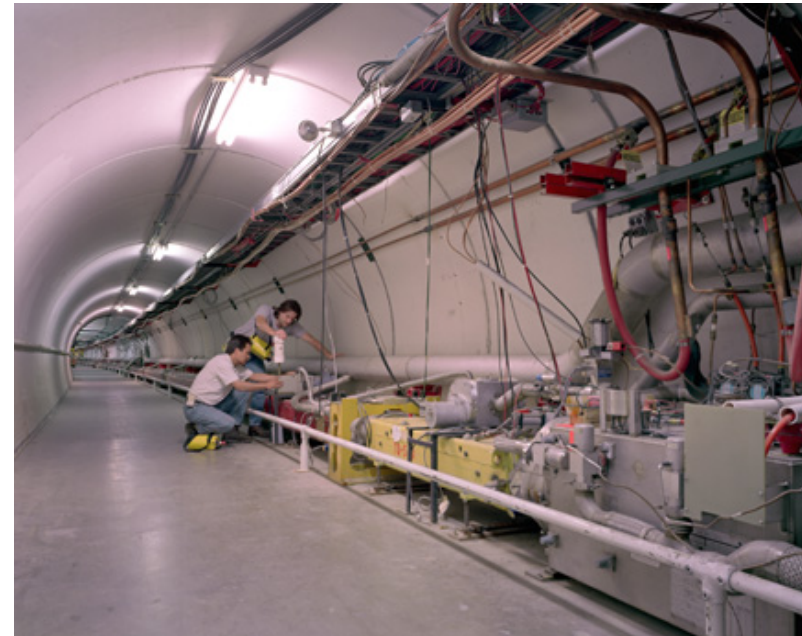
Fermilab Main Control Room

From here, control and monitor properties of all accelerators

around the clock operation, 24/7 all year
shut down periods occur, for maintenance

crews of 5-6 Accelerator Operators and Crew Chief

The Future…

Compare hadrons and leptons
- constituent hadron collision energy is about 1/10 of total hadron beam energies (protons made up of quarks!)
- constituent lepton collision energy is all of total lepton beam energies

Great growth in accelerator- based science during past half-century.

Slower in recent years…
- projects have become large
- necessarily international
- using same old technology

However, present projects require many people and offer many opportunities
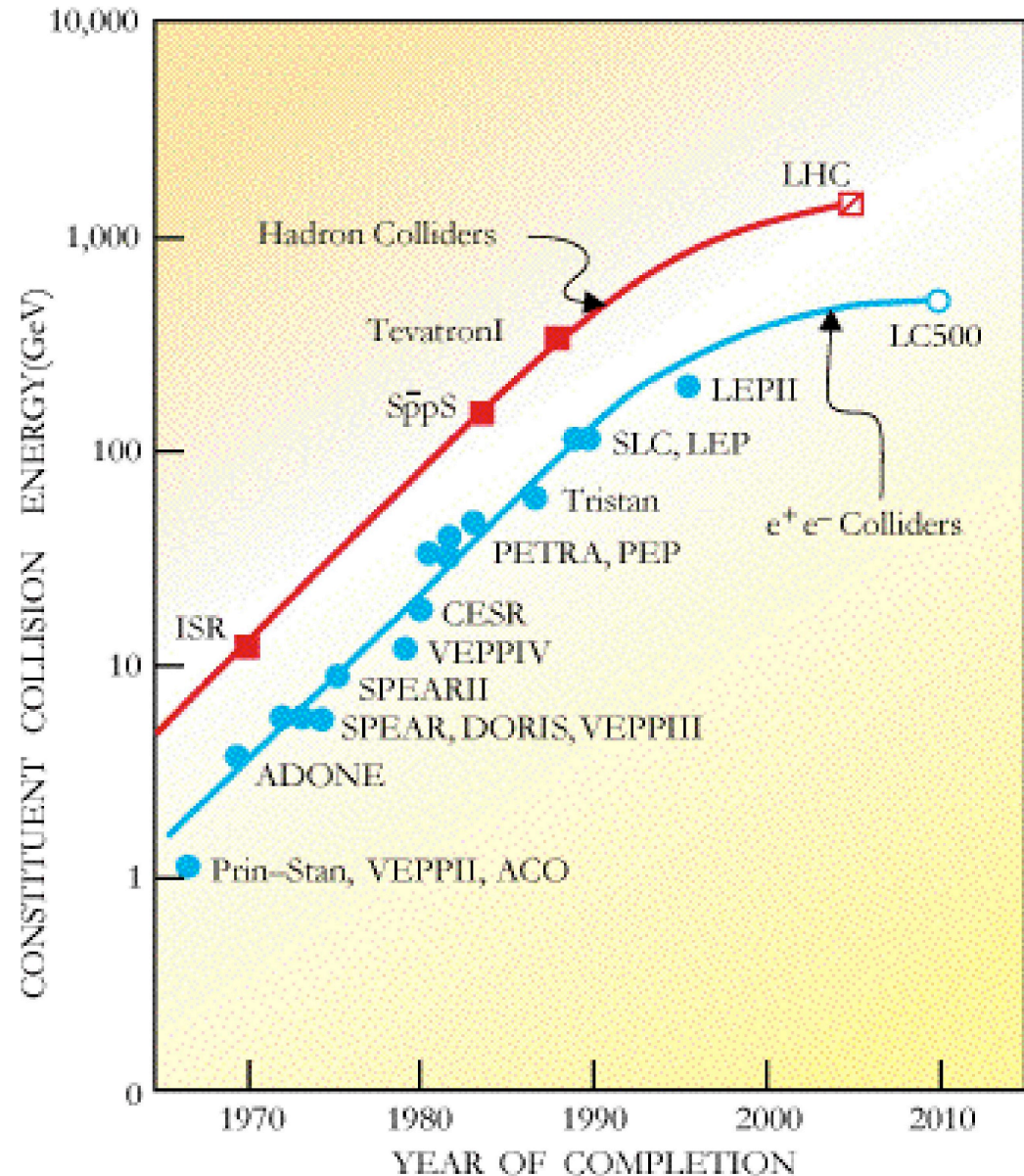
Current Accelerator R&D

- Large Hadron Collider (LHC)
  - Proton-proton collider, being constructed at CERN (Geneva, Switzerland)
  - 7000 GeV per particle;   note: protons contain quarks and gluons
  - Ready in ~1 year


Large Hadron Collider (LHC)

Current Accelerator R&D

- Large Hadron Collider (LHC)
  - Proton-proton collider, being constructed at CERN (Geneva, Switzerland)
  - 7000 GeV per particle;   note: protons contain quarks and gluons
  - Ready in ~1 year   ("messy" collisions)
- International Linear Collider (ILC)   *Complimentary Projects*
  - Large international community looking into this project
  - Electron-positron collider, 250-500 GeV per particle
  - Lower energy than LHC, but fundamental particle probes!   ("cleaner" collisions)
- Muon Collider / Neutrino Factory
  - Use muons, which are point-like, but heavier than electrons
  - Muons decay, generating neutrinos; good for neutrino studies?
- Very Large Hadron Collider
  - More of the same (like LHC), only *VERY* big…
- Plasma acceleration, Wake Field accelerators, …
- Other???

A balanced plan for the future

- Maintain strong presence at the energy frontier with the LHC, and continue to study / design possible future new collider at Fermilab

- Build up higher intensity beams (more particles) for frontier research at today's Fermilab energies

- Use our strong resources at the cosmic frontier with particle astrophysics and astronomy

- Fermilab plays a leadership role at all three of these forefront research directions.
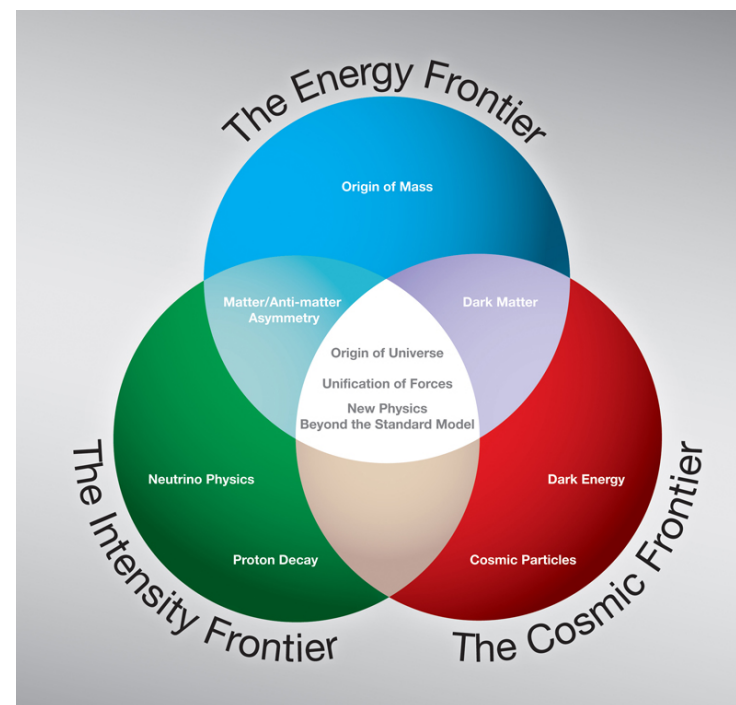
Fermilab continues to be a world leader in accelerator-based particle physics

Summary

- Controlled experiments to study fundamental high energy particle physics rely on accelerators
- Highest energy accelerator in the world is at Fermilab -- soon to be eclipsed by CERN's LHC …
  - Still, the center for neutrino physics experiments for some time!
  - Gearing up to perform other "precision" experiments at the energies accessible by our accelerators

- Meanwhile, Fermilab continues to work on future projects which can be funded at reasonable cost to best benefit the High Energy Physics community (and, society!)
 - LHC, International Linear Collider, etc.

References

- D. A. Edwards and M. J. Syphers, *An Introduction to the Physics of High Energy Accelerators*, John Wiley & Sons (1993)
- S. Y. Lee, *Accelerator Physics*, World Scientific (1999)
- E. J. N. Wilson, *An Introduction to Particle Accelerators*, Oxford University Press (2001)

- Web sites:
  - Particle Adventure
    - http://particleadventure.org
    - http://www.lbl.gov/Education/   (many other links here)
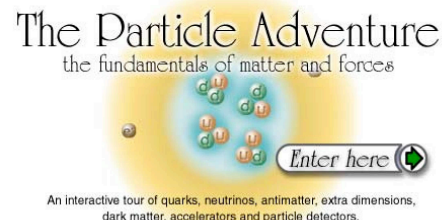
- Particle Accelerator Schools --
  - USPAS: http://uspas.fnal.gov
  - CERN CAS: http://cas.web.cern.ch

- Conference Proceedings   (use *Google!*) --
  - Particle Accelerator Conference (2007, 2005, 2003, …)
  - European Particle Accelerator Conference (2008, 2006, …)

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